

LASER DESIGN

A cooler Raman laser

Textbooks suggest that heating, caused by phonon emission, is an inevitable and intrinsic by-product of light generation in a Raman laser. Now a design has emerged that reduces the phonon emission and may lead to higher efficiency and smaller devices.

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Power dissipation, which results in heat generation in electronic chips, is the number one difficulty facing the semiconductor industry. The problem is so severe that it threatens to halt the huge development that has been enjoyed since the microprocessor industry's inception — a doubling in processor performance roughly every 18 months, which was predicted by the celebrated Moore's law. And this obstacle is not unique to microprocessors. The laser, another technological marvel that we rely on so heavily in today's world, is plagued by the very same problem. Now, however, Nathalie Vermeulen and colleagues have proposed a way of reducing unwanted heat generation in an important class of laser, the Raman laser¹.

The essence of the dilemma sounds almost trivial, but its solution has eluded scientists for decades. The optical power produced by most lasers is only a small fraction of the power they consume, and the rest is wasted as heat. The problem is most severe in optically pumped lasers — the high-power workhorses of industrial material processing, medicine, directed-energy weapons and scientific research. This predicament is particularly difficult because it originates from fundamental physics rather than a technological imperfection. The source of heating is the so-called quantum defect: the output (Stokes) photons have lower energy than the input (pump) photons. The difference in energy unavoidably goes into heating the medium. This energy loss and associated temperature rise decreases the lasing efficiency and leads to other undesirable effects, such as deterioration of beam quality through a process known as thermal lensing. The problem is exacerbated by another inconvenient principle: as the temperature

of the laser medium rises, its thermal conductivity drops. In other words, the hotter it becomes, the more heat it retains. This undesirable feedback can, in its worst form, damage or even destroy the lasing medium. To deal with this, high-power lasers must usually be equipped with elaborate cooling mechanisms, the cost, complexity and size of which can dwarf those of the laser itself.

Vermeulen and colleagues¹ have now proposed a solution to reduce heat generation in powerful optically pumped Raman lasers that generate wavelengths beyond the reach of other lasers. Their approach, an intrinsic heat mitigation mechanism, exploits an elegant nonlinear phenomenon called coherent

anti-Stokes Raman scattering (CARS) to minimize the heat generated by the quantum-defect phenomenon. If it can be realized in practice, this approach may improve the performance, reliability and lifespan of Raman lasers. By reducing the need for thermal management, it also has the potential to facilitate device miniaturization.

In Raman lasers, light amplification is based on stimulated Stokes Raman scattering (SSRS), a process in which atomic vibrations (phonons) in the medium mediate the transfer of power from the pump light at a frequency of ω_p to the output (Stokes) beam with a lower frequency of ω_s . This process, shown in Fig. 1a, leaves the medium in the excited

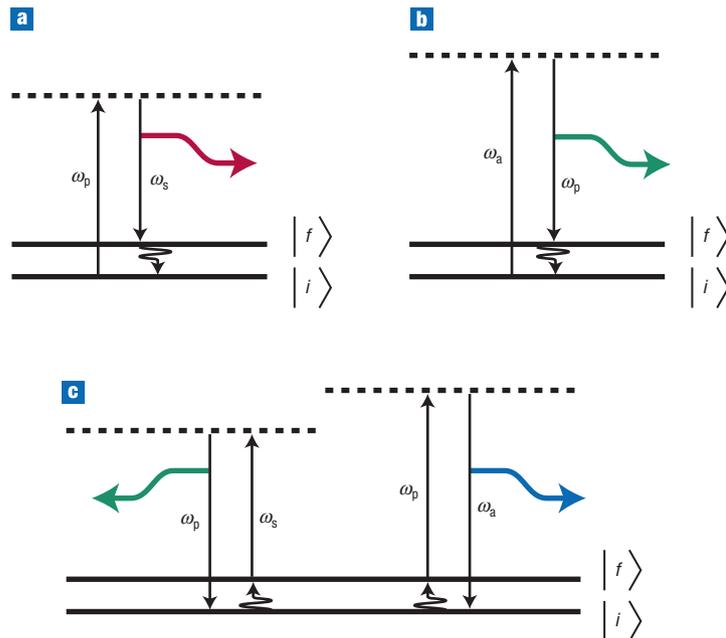


Figure 1 Processes that occur in a Raman laser. **a**, Stimulated Stokes Raman scattering produces one phonon. **b**, Stimulated anti-Stokes Raman scattering also produces a single phonon. **c**, Resonant Raman four-wave mixing, also referred to as CARS, removes two phonons from the medium. It is important to note the separation of these three individual processes is somewhat artificial: CARS cannot occur in the absence of the other processes². $|i\rangle$ and $|f\rangle$ are the initial and final states respectively. Figure reproduced from ref. 1. Copyright (2007) APS.

vibrational state. In other words, a phonon (and therefore heat) is generated every time a photon is created; there is a tax to be paid for every photon-producing transaction. The magnitude of this tax is the energy lost to heat, $\hbar\omega_v$ (where ω_v is the vibrational resonant frequency of the molecular bonds and \hbar is the reduced Planck's constant). It ranges from 64 meV per transaction in silicon to more than 1 eV per event for light atoms such as hydrogen. The tax rate is the ratio of the phonon to photon frequencies, ω_v/ω_s , multiplied by the relative number of quanta produced, N_v/N_s . Now, Vermeulen and co-workers have shown theoretically that there need not be a one-to-one correspondence between the number of photons and phonons, in other words N_v/N_s can be made less than one. Such a laser would produce less heat than a conventional Raman laser when generating the same number of output photons.

This counterintuitive result can be understood by realizing that SSRS is only one of three processes that take place in a Raman laser^{1,2}. The second process, depicted in Fig. 1b, is stimulated anti-Stokes Raman scattering (SARS), a process in which an anti-Stokes photon of frequency $\omega_a = \omega_s + \omega_v$, if present, is converted to a lower-energy pump photon plus a phonon. Thus, SARS also generates a heat-producing phonon. The third process, shown in Fig. 1c, is resonant Raman four-wave mixing, also known as CARS. This process transfers a low-energy Stokes photon to a higher energy anti-Stokes photon, while de-exciting the medium by the removal of two phonons. The reverse CARS process can also occur, exciting the medium by creating two

phonons, as can be visualized by reversing the direction of the arrows in Fig. 1c. In the absence of phase matching, CARS oscillates between forward and reverse processes along the beam-propagation direction. Phase mismatch in CARS describes momentum conservation in the four-wave-mixing scattering process and is defined in terms of the wavevector, $k = 2\pi/\lambda$, as $\Delta k = 2k_p - k_s - k_a$, where the subscripts 'p', 's' and 'a' refer to pump, Stokes and anti-Stokes photons. When the CARS process is phase matched, $\Delta k = 0$. The important point is that unlike conventional electronic four-wave mixing, which is an elastic scattering process, the Raman-resonant four-wave mixing is accompanied by transfer of energy between the light beams and the medium.

The heat-mitigation approach now proposed by Vermeulen *et al.* is best realized under phase-matched conditions. Let us assume that initially no anti-Stokes photons are present whereas a small number of Stokes photons exist owing to spontaneous emission produced by the pump beam. The initial Stokes photons cause the generation of additional photons through SSRS (Fig. 1a). At the same time, Stokes photons are annihilated by the forward CARS process, which converts them to anti-Stokes photons (Fig. 1c). As the number of anti-Stokes photons increases, SARS begins to convert them into pump photons (Fig. 1b). The pump photons are in turn converted to Stokes photons by SSRS, and so on.

The net result is that the number of excess phonons generated by the production of Stokes photons can be reduced by promoting production of anti-Stokes photons. Such a laser wastes less energy as unwanted heat, and instead

outputs both Stokes and anti-Stokes radiation. Vermeulen and co-workers compute the heat-mitigation efficiency as the ratio of the generated anti-Stokes to Stokes photons. They carry out the computation for two types of Raman gain media — hydrogen and silicon — and find impressive heat-mitigation efficiencies of 30% for hydrogen and 35% for silicon.

The fact that some of the pump energy is converted to the anti-Stokes wavelength may not be an issue for applications that rely on non-resonant or weakly resonant processes, which are not very sensitive to wavelength. The dual wavelength emission may even be a welcome feature in sensing applications where differential detection improves the detection sensitivity. On the other hand, if only the Stokes wavelength is desired, then the laser will require a higher pump power to compensate for the power that is transferred to the anti-Stokes wavelength.

One potential drawback is that the radiated energy increases only linearly with the length of the medium in phase-matched CARS, whereas it increases exponentially in a normal Raman laser. Thus, larger laser cavities may be required to produce adequate power levels. As optical dissipation increases in larger cavities, it remains to be seen whether the present technique can be implemented practically to mitigate the excess heating problem that has challenged laser designers and users. Nevertheless, the work of Vermeulen *et al.* proposes a solution to a problem that is in need of fresh ideas.

References

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